# ANALYSIS OF AIR MASS DEPENDENCE OF THREE PHOTOVOLTAIC ARRAYS

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ABSTRACT: The solar spectrum, which is also could be described by air mass factor, has a significant relationship with the performance of photovoltaic modules. The air mass dependence has been investigated by a theoretical method as well as an actual case of three different photovoltaic arrays: polycrystalline silicon, amorphous silicon and cadmium telluride, at the EUIT Agrícola-UPM (Madrid, Spain, 40.4426°N, 3.7295°W). The calculating results show that: AM dependence of poly-Si array is positive because an elevating AM-value indicates a red shift and poly-Si module is more red sensitive; On the contrary, as a-Si module and CdTe module are more blue sensitive, their AM dependences are negative. Furthermore, the outdoor AM dependences of three arrays are corresponding to the calculating results although the thermal annealing effect could be superimposed on spectral effect in the case of a-Si.
Keywords: PV system, spectral response, polycrystalline silicon, a-Si, CdTe

## 1 INTRODUCTION AND OBJECTIVS

In outdoor conditions, the two main meteorological issues affecting the electricity production of a PV module are the irradiance and ambient temperature. Besides, seasonal variation in solar spectrum contributes to the seasonal changed irradiance. Therefore, seasonal variation in PV module´s output could be influenced by the overlap of thermal effects and spectral changes [1–5]. Since different semi-conductor materials have different band gaps, they vary in response to radiation of different wavelengths, thus vary from each other both in efficiency and spectral response. On the other hand, the spectral components of solar radiation also have a seasonal change: they are blue-rich in summer and red-rich in winter respectively [6]. Commonly, solar spectral irradiance distribution can be characterized by three approaches: average photon energy [1], useful fraction [7], and air mass (AM) [8], which is the path-length through the atmosphere and used in this study.

In this study, the theoretical and the outdoor AM dependences of three different arrays: polycrystalline silicon (poly-Si), amorphous silicon (a-Si) and cadmium telluride (CdTe) are investigated.

## 2 MATERIALS AND METHODS

### 2.1 Air mass

The term ´´air mass´´, which is obtained through geometrical consideration, describes the relative path length that the sun’s rays traverse through the atmosphere. It can be a specific substitute in the absence of experimental spectral measurements on solar irradiance, although it is without the consideration of the vapor, turbidity and air pollution. The simplest formula (1) for calculating the pressure corrected AM [8] is just related to the position of the sun in the sky and the site altitude. Complex mathematical expressions of the AM provided by [8] and (Gueymard 1995) show no difference between equation (2) at zenith angles less than 80° [10].

$$AM = \cos(Z_s)^{-1} * \frac{P}{P_0} \quad (1)$$

$$\frac{P}{P_0} = \exp(-0.0001184 * h) \quad (2)$$

Zs: sun´s zenith angle, calculated based on [11]

Where:

P: local air pressure;

P0: sea level air pressure;

h: altitude, 650m of Madrid;

The solar spectral irradiance data shown in Figure 1 were simulated by the application of SMARTS (Simple Model of Atmospheric Radiative Transfer of Sunshine) developed by Gueymard. The normalized spectral responses of different technologies were provided by the accredited independent laboratory (CIEMAT-DER, Madrid).

### 2.2 Theoretical mathematical model:

The short circuit density of the three PV technologies could be calculated by:

$$\mathrm{Jsc} = \int E_\lambda^{Am}(\lambda) \cdot SR(\lambda) \cdot d\lambda \quad (3)$$

Jsc: short circuit current density of the test module;

$E_\lambda^{Am}(\lambda)$: spectral irradiance of the sunlight at different AM values;

$SR(\lambda)$: spectral response of the test module;

## 3 RESULTS AND DISCUSSIONS

### 3.1 Calculating results

The calculating results based on equation (3) and Figure1, are demonstrated in Figure 2 and 3.

Figure 2 is simulating the results obtained from a pyranometer. In this case, the AM dependence of poly-Si is positive, whereas the Isc of a-Si and CdTe would decrease with the rising AM values.

Figure 3 is simulating the results obtained from a c-Si based irradiance sensor. Consequently, there is no AM dependence in the Isc of poly-Si. However, the Isc of a-Si and CdTe decline faster with the rising AM value.

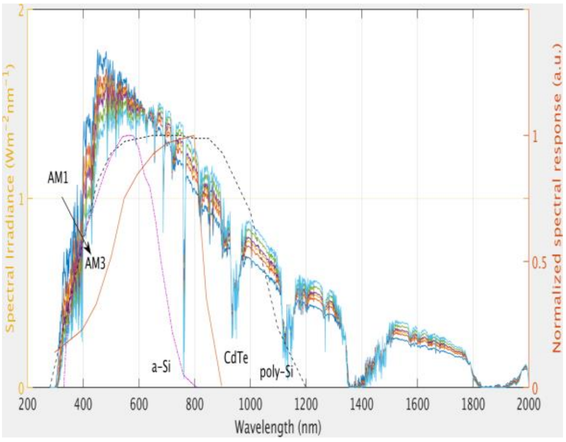


**Figure 1:** Simulated solar spectrum and spectral response of different technologies.

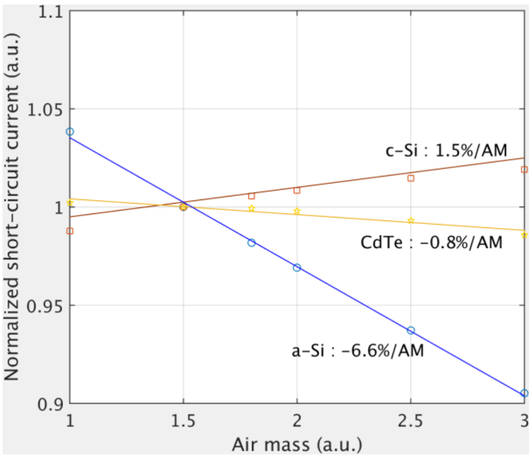


**Figure 2**. Calculating results of three technologies as the irradiance sensor is a pyranometer.

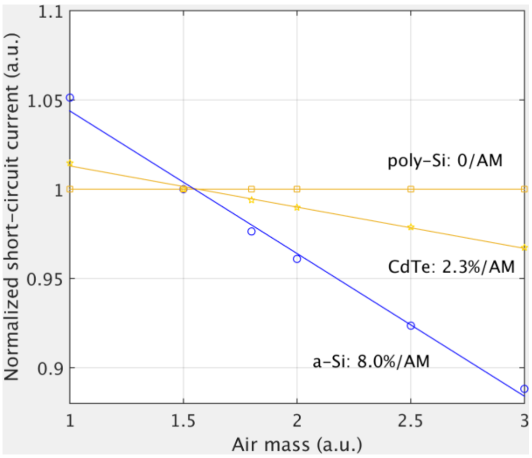


**Figure 3**. Calculating results of three technologies as the irradiance sensor is a c-Si based sensor.

### 3.2 Outdoor results

As pre-mentioned, AM is calculated by a geographical consideration and fails to contain the weather information, which also affects the spectral distribution. Thus a pre-clarification about the weather condition or a uniform weather condition should be decided. All the data shown in Figure 4 was collected under clear-sky condition and then corrected and normalized:

- Clear-sky condition: the variation of the irradiance is less than 10% from the maximum value to the minimum value recorded during the 15-min recording interval;
- Irradiance range: the reason of choosing the irradiance level at 700W/m$^2$ is inverter clipping happens occasionally once the irradiance is beyond 800W/m$^2$, subsequently the Pmp would be affected;
- Correction and normalization: the maximum power was linearly corrected to the condition (G=1000W/m$^2$, Tc=25$^o$C) using the maximum power (Pmp) temperature coefficient provided by the manufacturers, and then divided by the linear fitted value at AM1.5.

Figure 4 shows the AM-dependence of the Pmp of the three arrays from December 2014 to December 2015. The higher AM values indicate the solar spectrum tending towards the redder or longer wavelength.

As depicted in Figure 4, in both the irradiance ranges, the AM-dependence of Pmp for poly-Si, CdTe and a-Si arrays increased successively. The regression line parallel to x-axis in Figure 4a indicates no clear AM-dependence of Pmp generated by the poly-Si array, owing to a c-Si based reference irradiance sensor and the determinate irradiance range. The AM-dependence of Pmp for a-Si and CdTe arrays is stronger, suffering a decreasing trend for higher AM values (red-shift). The gradient of the applied linear least square fit can also provide information about the AM-dependence. Comparing the two irradiance ranges, the AM-dependence of Pmp follow the same pattern for each array. Pmp for a-Si array varies at a higher rate ~11.22% compared to the ~4% variation of the CdTe array´s Pmp, due to the narrower and more blue-sensitive spectrum response. Note that these AM-dependences for a-Si and CdTe are based on a c-Si irradiance sensor. Furthermore, as is shown in Figure 4c, the notable gap between the Pmp gathered from two periods, i.e. Apr.2015 –Jun.2015 and Jun.2015 – Sep.2015, suggests there are some other factors contributing to the seasonal variation of a-Si, besides the changeful AM. It will be explained by *thermal annealing effect* and *light soaking effect*.

## 4 CONCLUSION

- No detective air mass (AM) dependence of poly-Si array has been found owing to the application of c-Si based irradiance sensor, whereas the calculating result shows that poly-Si has a positive AM dependence;
- a-Si has the highest AM dependence among the three technologies, although there is an overlap of *thermal annealing effect* and spectral effect in a-Si array;
- AM dependence of CdTe array is lower compared to the value of a-Si array, due to the more red-sensitive spectrum response.

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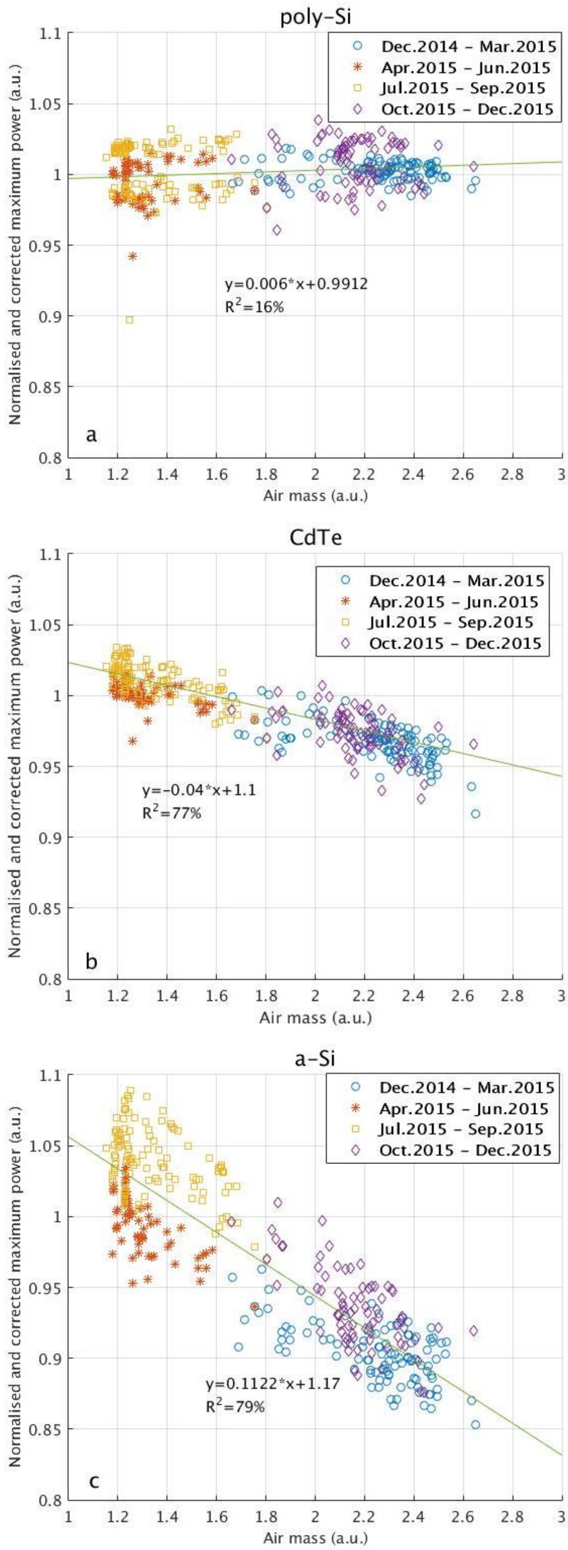


**Figure 4**. Seasonally classified maximum power dependence on AM-units for the poly-Si (a), a-Si (b) and CdTe (c) array under clear-sky condition.

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